High-Resolution Seismic Velocity and Attenuation Models of the Caucasus-Caspian Region

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14. ABSTRACT

The Caucasus-Caspian region is part of the Alpine-Himalayan collision belt and is an area of complex structure accompanied by large variations in seismic wave velocities. Using data from 29 new broadband seismic stations in the region as well as data from a temporary (1999-2001) deployment in eastern Turkey, a unified velocity structure is developed using teleseismic receiver functions and surface waves. Joint inversion of surface wave group dispersion curves generated from ambient noise with receiver functions show that crustal thickness varies from 34 to 52 km in the region. The thickest crust is in Lesser Caucasus and the thinnest is in the Arabian Plate. Thin crust is also observed near the Caspian. The lithospheric mantle in the Greater Caucasus and the Kura depression is faster than the Anatolian Plateau and Lesser Caucasus. This possibly indicates the presence of cold lithosphere. The lower crust is slowest in the northeastern part of the Anatolian Plateau where Holocene volcanoes are located. Fundamental mode Rayleigh wave phase velocities are determined at periods between 20 and 145 seconds. We observe a relatively high velocity zone located in the upper mantle under the Kura basin and the western part of Caspian Sea that is continuous to the Moho. The images show very low velocities beneath the eastern Anatolian plateau implying the existence of a partially molten asthenospheric material underlying a very thin lithosphere. Using a two-station method, both Lg and Pg attenuation is measured and tomographically inverted to yield attenuation maps. Efficient Lg propagation is observed throughout much of the Arabian plate. Moderate Lg Q is observed in the Lesser Caucasus and Kura Basin while low Lg Q is observed in the East Anatolian plateau. Pg shows highly variable propagation throughout the region.

15. SUBJECT TERMS
Caucasus, Velocity structure, Seismic

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1. SUMMARY

In 2007, San Diego State University (SDSU) was awarded a contract by the Air Force Research Laboratory to develop high-resolution seismic velocity and attenuation models of the Caucasus/Caspian region. This region displays significant velocity and attenuation heterogeneities as well as anomalies in regional phase propagation (*Lg*, *Pn*, *Sn*) anomalies and large errors in global earthquake locations. Therefore, an improved understanding of the seismic velocity and attenuation structure was desirable. This work was done in collaboration with personnel at Lawrence Livermore National Laboratory (LLNL) and University of Missouri, as well as international collaborators at the Republic Seismic Survey, Baku, Azerbaijan; Kandilli Observatory, Istanbul, Turkey, and the Georgian Seismic Survey in Tbilisi, Georgia. The objective of the research is to develop 3D seismic velocity structure and regional phase attenuation models for the Caucasus-Caspian region. The work consisted of four main tasks: data collection, regional phase analysis, crustal and upper mantle velocity determination, and model validation. Waveform data was collected from 33 new broadband stations in the region as part of collaborative effort with the individual seismic surveys. The primary focus was collecting continuous data from 2006-2008, although waveform data from other years was collected as available. All data has been provided to the Knowledge Base at LLNL. To develop a comprehensive model of crustal and upper mantle velocities, joint inversion of receiver functions and surface waves was applied. Both earthquake event data and ambient noise methods were used to estimate surface wave dispersion. *Pg* and *Lg* attenuation maps were developed using a two station-method combined with inversion. *Sn* propagation was mapped using a semi-quantitative method. Velocity model results showed Moho depths ranging from 35 to 55 km and substantial variations in crustal structure. The upper mantle possessed anomalously low velocities under the Anatolian plateau and was faster under the northern edge of the Arabian plate and the Kura depression. Both *Lg* and *Pg* displayed strong lateral variations. Sn propagation roughly corresponded with upper mantle velocity variations. Validation was performed by earthquake locations using events located near stations. The improved model showed improved residuals over previous models.

2. INTRODUCTION

2.1 Objectives and justification

The Caucasus-Caspian region is an area of complex structure accompanied by large variations in seismic wave velocities and attenuation. In such areas, accurate geophysical models are fundamentally important to nuclear monitoring for two reasons: improved event location and path calibration (critical for accurate estimation of event size and mechanism). In particular, the great thickness and irregular geometry of the low velocity and low density sediments in the Caspian and Black Sea basins causes profound effects on seismic waveforms, especially on surface waves and regional phases. These effects are compounded by variations in crustal structure in the Caucasus and by high attenuation under the E. Anatolian plateau (*Sandvol et al.,* 2001). A high resolution model is necessary to adequately capture the extreme variability in this region, as regional models based on widely spaced stations may suffer from insufficient spatial sampling. In recent years, new broadband seismic stations have been installed in the region (Figure 1). By forging collaborations with the institutions operating these stations, access to these data have been obtained.

2.2 Project team

The project team consisted of 3 principal investigators (Table 1) along with collaborating individuals from Kandilli Observatory (Dr. Niyazai Turkelli and Ugur Teoman), Azerbaijan Seismic Survey (Gurban Yetirmishli), and Georgian Seismic Center (Dr. Tea Godaladze and Dr. Zurab Javakhishvili). Several graduate students from San Diego State University (Rumi Takedatsu and Jason Ricketts) and Missouri (Gleb Skobeltsyn) also worked on the project.

Table 1. Project Team (lead investigators)

Name	Responsibilities
Dr. Robert Mellors SDSU	Overall project management and reporting duties. Receiver functions and validation.
Dr. Rengin Gok LLNL	Joint inversion; dispersion measurements; data product integrator.
Dr. Eric Sandvol UM	Regional phase attenuation; phase velocities; oversight of graduate students

2.3. Data delivery.

All waveform data (Table 2) was delivered to the Knowledge Base Product Integrator (R. Gok) at LLNL along with instrument/datalogger responses. Most data was provided on portable hard drives in either miniseed or SAC format. Dates of delivery varied from Spring 2007 to Summer 2009.

Table 2. Waveform data acquired

year	Azerbaijan			Georgia			Turkey	
	Trig.	*Cont.*	*Rate*	*Trig.*	*Cont*	*Rate*	*Cont*	*Rate*
2003	106		50					
2004	47		50					
2005		88	1	21		100		
2006	109	161	50,20	31		100	95	50
2007	189	94	50,20		365	100	356	50
2008	83	47	50,20		366	100	39	50
2009	22	56	50,20					
Total days	*556*	*446*		*52*	*730*		*490*	

3. TECHNICAL APPROACH

3.1 Data Collection

Most data exchange occurred during visits of U.S. investigators to Baku, Tbilisi, and Istanbul (2007, 2008, and 2009) and during reciprocal visits of collaborators to the US. Data was collected on portable hard drives as quantities (typically 10's of GB) were too large for transmission by internet. These trips included considerable scientific collaboration on topics such as receiver functions processing and earthquake location. In addition, a Kandilli graduate student (Ugur Teoman) visited the U.S. for several months in 2008 and worked at Missouri. A Georgian scientist (Dr. Tea Godaladze) also visited at that time. In December 2008 two Azeri members of the scientific staff visited the US to work at SDSU for two weeks. All data was collected at SDSU where it was reformatted into CSS format. From SDSU, data was provided to the other investigators as needed. Copies of data were also provided to the KnowledgeBase integrator (Dr. R. Gok) at
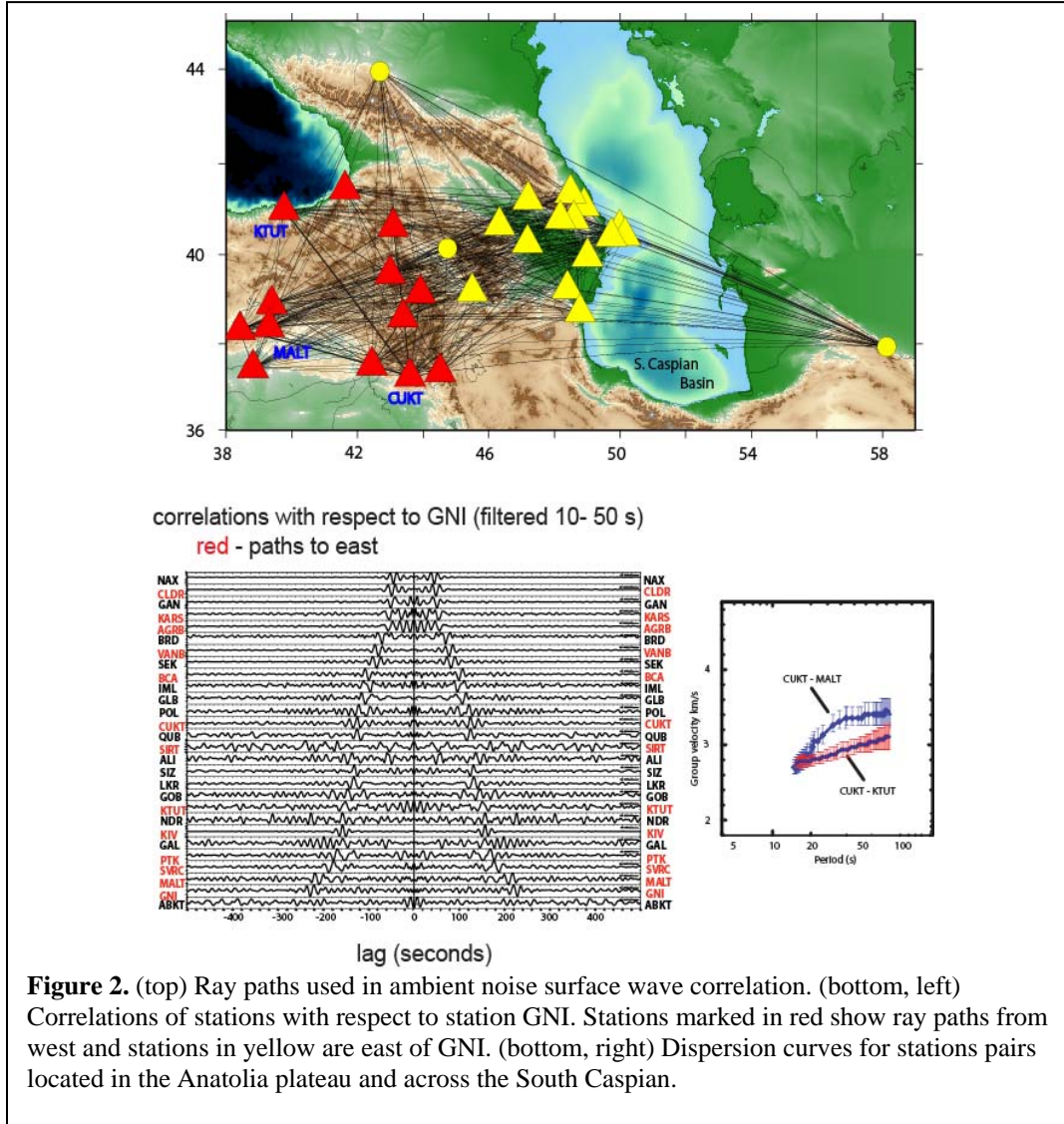
LLNL. Verification of instrument responses was conducted jointly. Data from global stations (KIV, GNI, and ABKT) was also included in the dataset at SDSU.

3.2 Crustal and upper mantle velocities

To develop a comprehensive model of crustal and upper mantle velocities, joint inversion of receiver functions and surface waves was applied. Crustal receiver functions are sensitive to velocity discontinuities while surface wave dispersion is controlled by average S-wave velocity structure. Therefore, combining the two methods yields a robust estimate of crustal and upper mantle velocities. Receiver functions using events at distances between 30 and 90 degrees were calculated for all stations using iterative deconvolution at Gaussian widths of 1.0, 1.5, and 2.5 seconds. Each receiver function (Figure 1) was examined for consistency and signals with excessive amplitudes on the tangential component or grossly different from the stacked average for each station was discarded. Coverage was best for back-azimuths to the east and sparse to the west. Initially, the receiver functions were modeled independently to investigate quality. The slant stacking of *Zhu and Kanamori* (2000) was also used to estimate Moho depths. In general, the stations near the Caspian show poor quality receiver functions with indications of considerable crustal scattering and reverberations due to the thick sediments. These were difficult to model. Some indications of 3D structure were observed for stations in the Greater Caucasus as the receiver functions showed clear variations with back azimuth. The stations on the Absheron Peninsula were also exceptionally noisy due to cultural and wind/water wave noise.
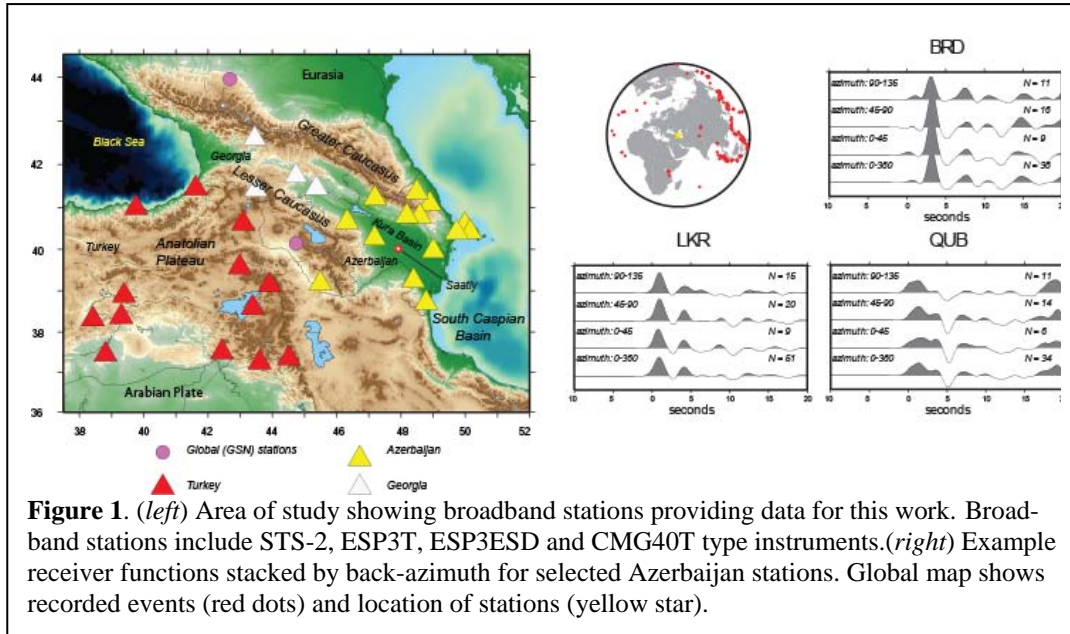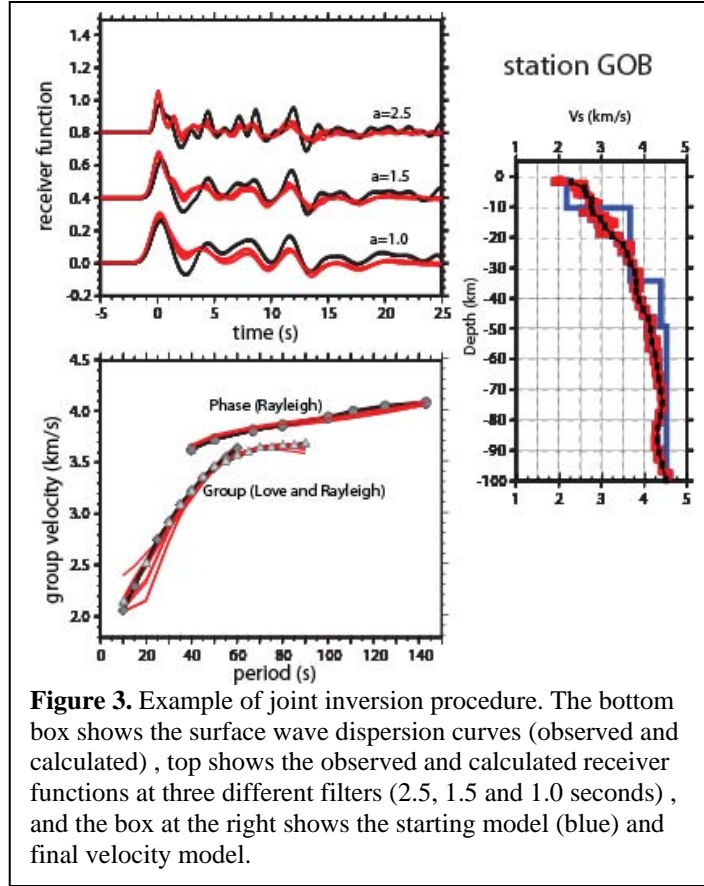

Figure 1. (*left*) Area of study showing broadband stations providing data for this work. Broadband stations include STS-2, ESP3T, ESP3ESD and CMG40T type instruments.(*right*) Example receiver functions stacked by back-azimuth for selected Azerbaijan stations. Global map shows recorded events (red dots) and location of stations (yellow star).

Figure 2. (top) Ray paths used in ambient noise surface wave correlation. (bottom, left) Correlations of stations with respect to station GNI. Stations marked in red show ray paths from west and stations in yellow are east of GNI. (bottom, right) Dispersion curves for stations pairs located in the Anatolia plateau and across the South Caspian.

Surface wave group velocity dispersion measurements were made using both event-based and ambient noise correlation methods (Figure 2). Love and Rayleigh wave group velocity dispersion curves were estimated for over 1500 waveforms at periods of 7-100 sec. Ambient noise correlation was applied to all possible station pairs (~400) to obtain Rayleigh wave group velocities. All dispersion curves were picked manually and then included in the global/regional tomographic inversion of *Pasyanos et al.* (2005). We then extracted the dispersion curves from the tomography maps of surface waves. The dispersion curves and stacked receiver functions were then jointly inverted using the methodology of *Julia et al,* (2000) (Figure 3).

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To investigate variations in upper mantle velocities, surface wave phase velocities measured from earthquakes were also inverted. Data from an earlier temporary deployment of 29 stations was used as well as the newer data. Teleseismic earthquakes with a magnitude greater than 5.8 were selected and the waveforms were evaluated for high signal to noise at the longer periods (50 and 125 seconds). Unfortunately, many of the Azerbaijan stations showed high noise levels at the longer periods even on the vertical component, possibly due to barometric variations. This

Figure 3. Example of joint inversion procedure. The bottom box shows the surface wave dispersion curves (observed and calculated) , top shows the observed and calculated receiver functions at three different filters (2.5, 1.5 and 1.0 seconds) , and the box at the right shows the starting model (blue) and final velocity model.
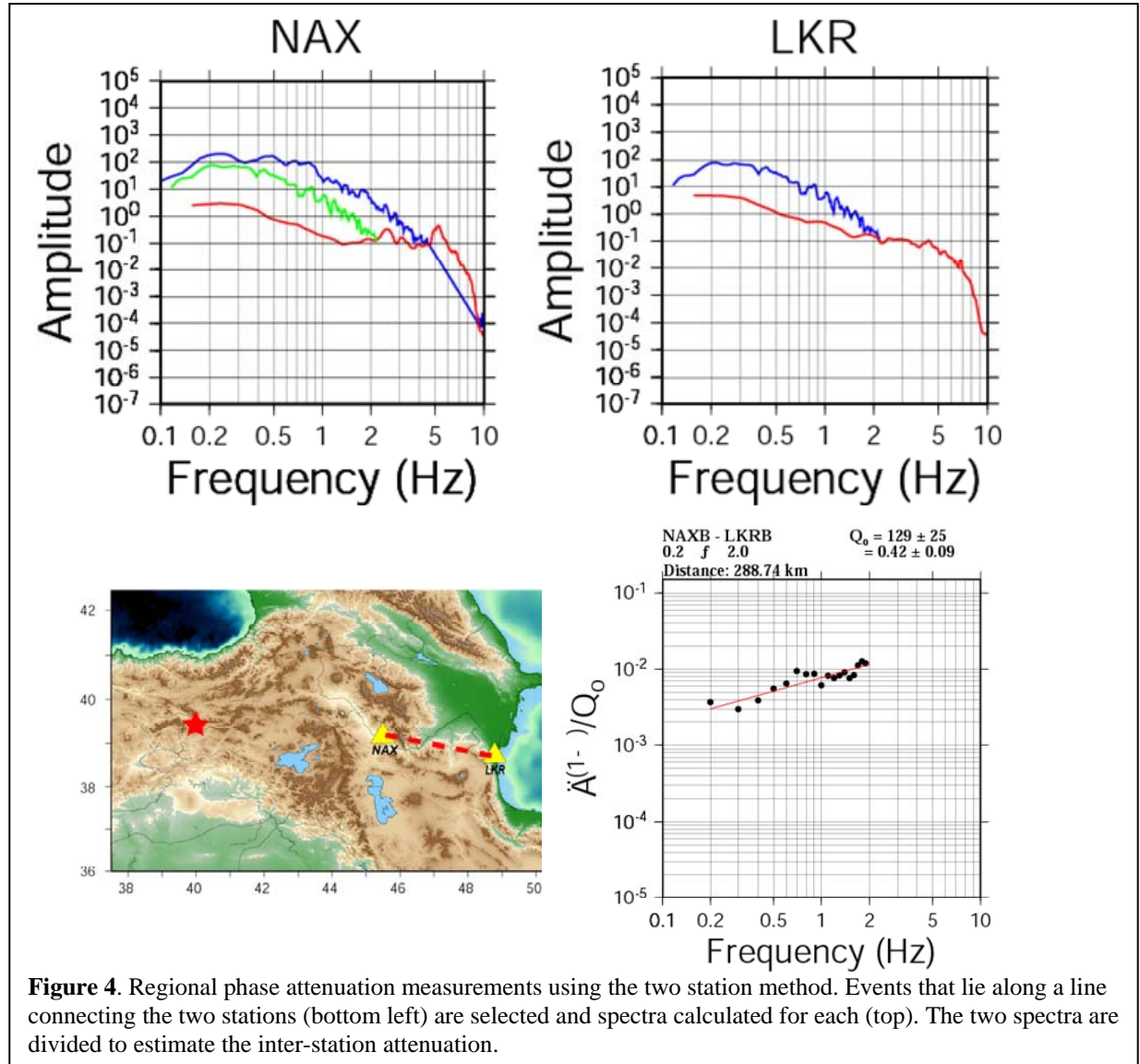
restricted the data set to 20 events. The data for each event were filtered to create 13 frequency bands with corresponding centered periods ranging from 20 to 145 seconds and dispersion curves were estimated from these results. Initially, the Rayleigh wave phase dispersion was inverted to estimate 1D velocities. The results were topographically inverted for 2D structure on a 50 km grid using two methods: *Forsyth et al*. (1998) and *Yang and Forsyth* (2006). The two methods are similar but the Yang and Forsyth technique attempts to compensate for scattering caused by local heterogeneities and therefore should improve spatial resolution. The results at shorter wavelengths were more robust than for the longer wavelengths especially for the area covered by the Azeri stations, possibly due to excessive noise at longer wavelengths.

3.3 Regional phase analysis.

The purpose of the regional phase analysis is to extend regional phase attenuation maps (e.g *Al-Lazki et al*., 2003; *Gok et al*, 2003) throughout Anatolia and the Caucasus (Figure 5). The mapping was performed by first measuring attenuation between stations and then inverting to solve for the average Q in discrete spatial cells. The direct two-station method was used (*Zor et al*., 2007; *Xie et al*., 2004) to estimate attenuation for each path. This method relies on spectral ratios between pairs of station aligned with the ray paths from each event. Phases were identified manually to avoid problems caused by

variations in crustal velocities. Spectra for each phase were estimated after windowing. Station pairs for each event were selected using a criteria based on inter-station distance and alignment with event (±15°). The spectral ratio between two stations was calculated for appropriate station pairs after correction for distance (*Xie et al.*, 2004) and geometrical spreading. Q and η (frequency dependence) were then estimated from the spectral ratios using linear regression (Figure 4). This Q and η represents the attenuation along a line between the two stations. These attenuation measurements were added to an existing Middle East dataset which was inverted to create a regional map. The dataset includes approximately 3000 station pairs. Separate inversions were conducted for both

Figure 4. Regional phase attenuation measurements using the two station method. Events that lie along a line connecting the two stations (bottom left) are selected and spectra calculated for each (top). The two spectra are divided to estimate the inter-station attenuation.
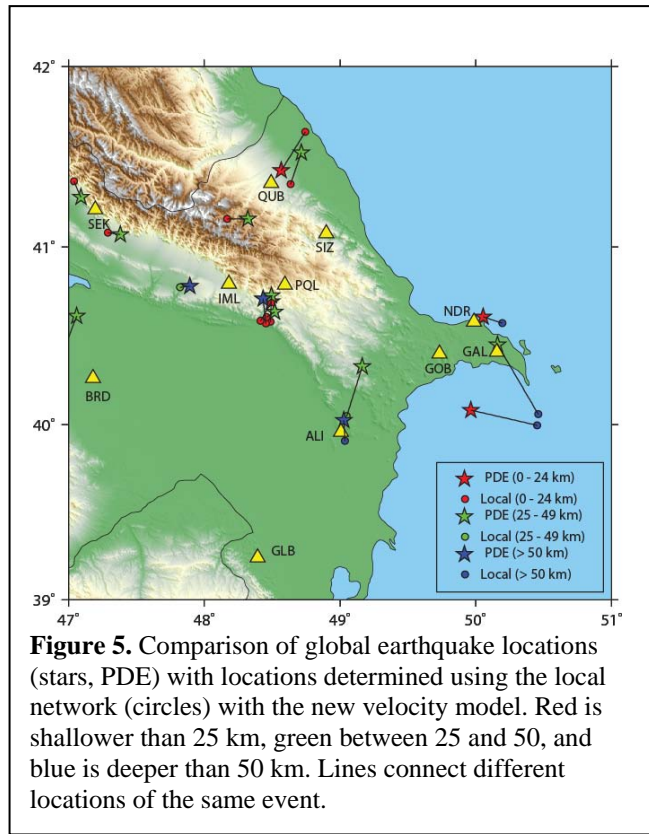
Lg and Pg. Checkerboard tests were performed to evaluate resolution and both ART and LSQR inversion algorithms were tested to evaluate the effect of possible numerical artifacts. Results were similar for both algorithms. Raypath coverage is good in eastern Anatolia but is sparser towards the Caucasus and Caspian.

3.4 Model validation

The model was tested in several ways: comparison with alternate datasets such as reflection seismic and gravity, earthquake hypocenters comparison, and with waveform modeling. Seismic reflection refraction data shows clearly the deep sedimentary layers in the South Caspian and coastline (*Knapp et al.*2004; *Mangino and Priestley*, 1998). Gravity data also suggests deep basement, which closely matches the low velocities for the area observed by the joint inversion. The Moho depths inferred by refraction data are also similar. 2D modeling of gravity data through the center of the Kura basin shows a clear gravity high that runs roughly north-south and parallel to the Caspian coast and delineates the Kura from the South Caspian. The existence of this basement high is confirmed by the Saatly deep well, which penetrated to a depth of 9 km through a succession of sediment and then volcanoclastic layers. To first order, alternate datasets are consistent with our results, both for crustal and mantle velocities and phase propagation.

A second set of tests was conducted with earthquake locations. This effort was focused in the Azerbaijan region. The 3D model was averaged to produce an average 1d model. Hypocenter locations were calculated using this model and compared with global PDE (Preliminary
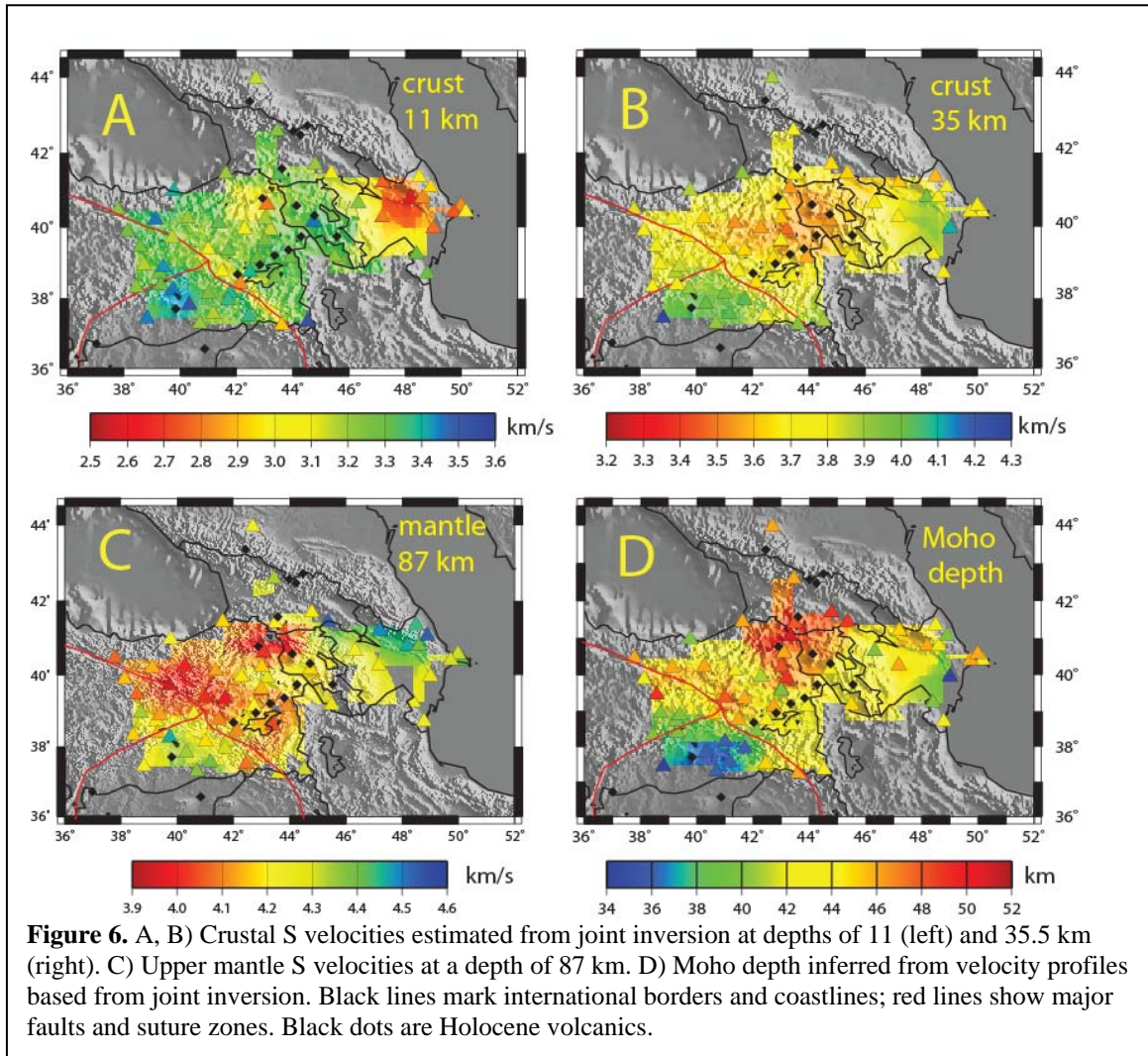

Figure 5. Comparison of global earthquake locations (stars, PDE) with locations determined using the local network (circles) with the new velocity model. Red is shallower than 25 km, green between 25 and 50, and blue is deeper than 50 km. Lines connect different locations of the same event.

Determination of Epicenters) locations. Significant differences in location were observed (up to 30 km) (Figure 5). A major factor is the exceptionally thick sedimentary package in Kura Basin and nearby South Caspian Basin. Waveforms for events with known focal mechanisms were also calculated using this model.

4. RESULTS AND DISCUSSION

Here we summarize the results of the analysis. Key elements from the joint inversion are shown in Figure 6, which displays horizontal depth slices of 11, 35 and 87 km and an estimated Moho thickness map. The thick sediments of the Kura Basin are evident in the upper crust with low velocities averaging Vs=2.8 km/s. The eastern part of the Greater
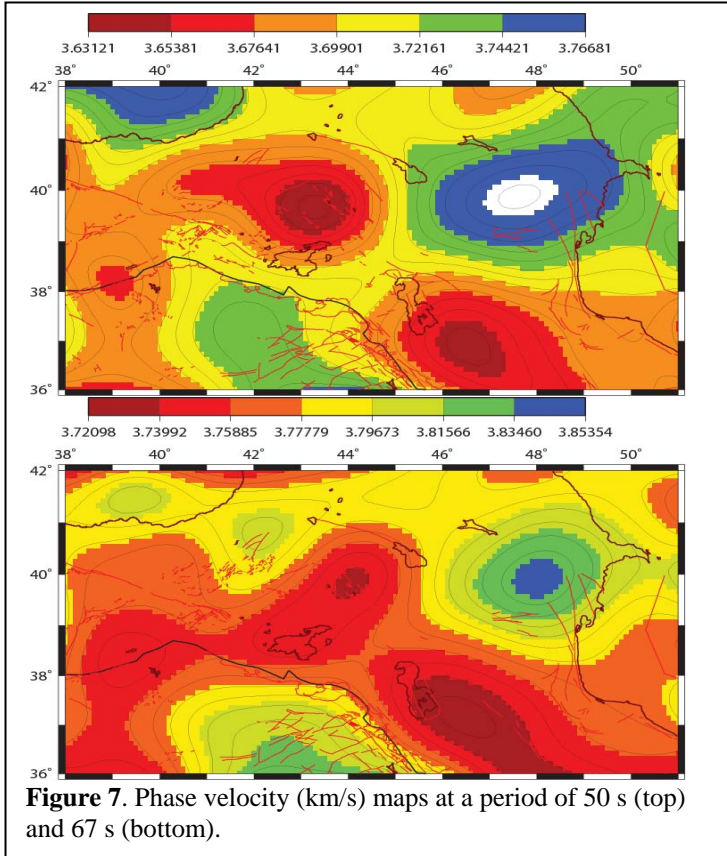
Caucasus shows similar low velocities in the upper crust. The slowest lower crustal velocities are observed in the northeastern Anatolian plateau and Lesser Caucasus region where considerable Neogene/Quaternary and Holocene volcanic activity has occurred. Faster lower crustal velocities occur at the edge of the Caspian and in the Arabian plate. The upper mantle appears distinctly slow under the Anatolian plateau and to the southeast. Indications of faster upper mantle velocities occur under the Greater Caucasus. It was noted that inversion for Love and Rayleigh waves provided slightly different results, possibly due to anisotropy. The anomalies continue into the upper mantle where a pronounced high-velocity zone is observed under the Kura Basin (Figure 7).

Figure 6. A, B) Crustal S velocities estimated from joint inversion at depths of 11 (left) and 35.5 km (right). C) Upper mantle S velocities at a depth of 87 km. D) Moho depth inferred from velocity profiles based from joint inversion. Black lines mark international borders and coastlines; red lines show major faults and suture zones. Black dots are Holocene volcanics.

As expected from the observed variations in the velocity models, regional phase attenuation varies over the region. The 1 Hz *Lg* results show a broad zone of high attenuation (low Q) extending roughly east-west north of the Arabian plate from Anatolia to the Caspian (Figure 5). Considerable spatial variation exists which likely reflects the
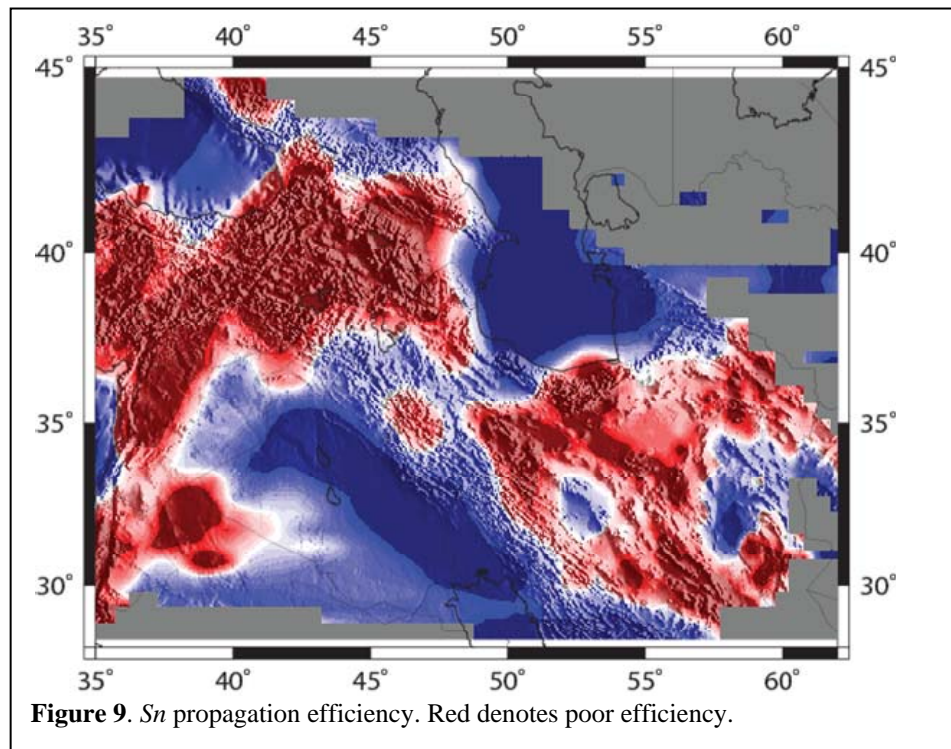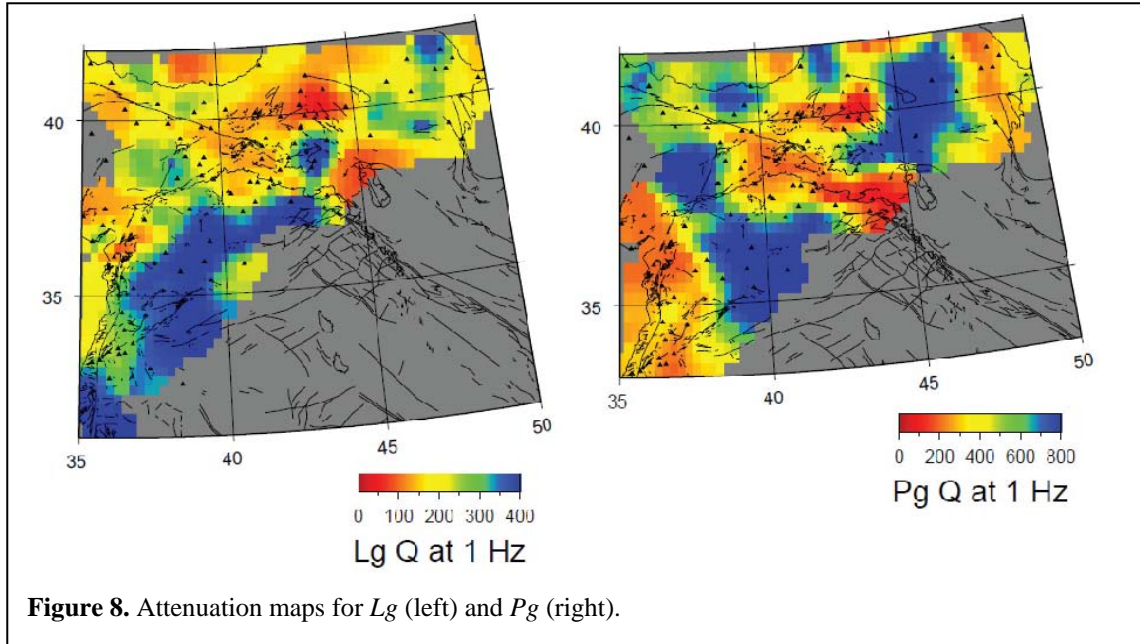
complicated tectonics. *Lg* appears to propagate well in the Arabian plate but is dramatically attenuated in the Lesser Caucasus. This may be due to the volcanism and the possibility of partial melt in the crust. The Kura basin and the extreme eastern Caucasus show moderate to low attenuation, which may reflect the influence of the Eurasia plate. It is clear from these results that the Kura basin is underlain by continental crust and is distinct from the South Caspian. The variations in *Lg* attenuation appear to result from a combination of both crustal heterogeneity and changes in crustal thickness. While Moho depth increases by 5 to 10 km at the northern edge of the Arabian Plate the variation in depth from Anatolia to the Lesser Caucasus is fairly small and yet relatively low *Lg* Q is observed. Volcanic regions are often observed to possess low *Lg* Q possibly due to high attenuation of shear waves by partial melt in the crust. *Pg* reveals a distinctly different pattern. The transition between the Arabian plate and Anatolian plateau is defined by an abrupt change in *Pg* Q east of about 38 E longitude but a clear zone of high Q exists in the Lesser Caucasus. The zone of low Q along the Caspian and Kura basin may be caused by the abrupt thickening in sediments and dipping Moho, which decreases the efficiency of the crustal *P* waveguide. *Sn* shows similar patterns of propagation efficiency which roughly correlate with upper mantle velocities (Figure 9).

Figure 7. Phase velocity (km/s) maps at a period of 50 s (top) and 67 s (bottom).

Figure 8. Attenuation maps for *Lg* (left) and *Pg* (right).

Figure 9. *Sn* propagation efficiency. Red denotes poor efficiency.

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5. CONCLUSIONS

An improved crustal and upper mantle velocity and attenuation model has been developed for the Caucasus/Caspian region and Anatolian plateau. The Caspian and Kura basins show pronounced low velocities in the upper crust but slightly elevated lower crustal velocities. Crustal thickness varies from about 50 km in the Lesser Caucasus to 35 km in the Arabian plate. The upper mantle displays strong heterogeneities in the region. It is slow under the Anatolian plateau and slightly fast under the Greater Caucasus. These are likely related to slab remnants and ongoing volcanism.

Striking variations in regional phase propagation and velocities are mapped. *Lg* is highly attenuated not only in the South Caspian and Black Sea basins but also in the Anatolian plateau, possibly due to a combination of crustal properties under the volcanic areas and varying crustal thickness. A clear change in *Lg* attenuation occurs at the northern edge of the Arabian plate. A narrow band of moderate *Lg* attenuation exists in the Kura basin and along the Caspian. *Pg* also shows variations in attenuation.

6. RECOMENDATIONS

Due to the strong spatial variations in both crustal and mantle properties, regional seismic waves should be expected to vary significantly both in travel-time and amplitude in this region. Additional seismic stations are scheduled to be installed in the region by the various surveys and this data would be useful in increasing the resolution of these results.

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List of Symbols, Abbreviations, and Acronyms

AFRL	Air Force Research Laboratory
LLNL	Lawrence Livermore National Laboratory
SDSU	San Diego State University
UM	University of Missouri